Size Distribution of Large Droplets in Precipitating Clouds

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(Manuscript received October 28, 1960, revised version July 10, 1961)

Abstract

Measurements have been made of the size distribution of large droplets in various clouds at a station situated on Mount Kuro. The results show that most nimbostratus, cumulus congestus and cumulonimbus clouds contain large droplets of radii above 50 μ. The spectral distributions fit fairly well the relation $N = N_0 r^{-\alpha}$ where α has values between 4 and 11. The concentration of large droplets varies widely and values above 10^5 per m^{-3} are frequently observed in precipitating clouds.

1. Introduction

Measurements of the size and number of cloud droplets have been made in a number of investigations, however, most of these have been concerned with non-precipitating clouds and there is still a lack of data with regard to precipitating clouds. The investigation described here reports on a number of measurements of the size distribution of large cloud droplets observed on Mount Kuro (altitude 1,900 m, see Figs. 1 and 2) in Hokkaido, Japan, during the summers of 1955—58.

2. Gravity settling method

In order to avoid the difficulties encountered when using impactor or oil or magnesium oxide coated slides (exposed vertically) for measuring sparsely distributed large droplets,

Fig. 1.

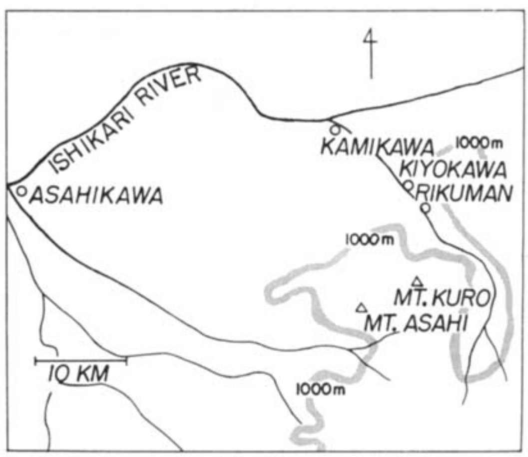

Fig. 2.

the following technique was adopted. Magnesium oxide coated glass slides or water-blue dye coated celluloid film strips (OKITA, 1958 a), having an area of 2×4 cm², were placed in a rectangular hole in the center of a thin, streamlined wooden plate of the size 30×30 cm², Fig. 3. During the measurements the

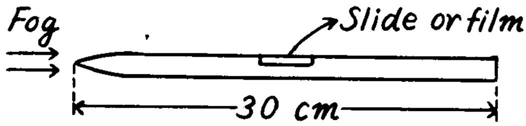

Fig. 3. Horizontal droplet sampler.

plate was kept in a horizontal position in the cloud air. When large raindrops fell, the plate was covered with a woolen cloth to prevent splashes from influencing the measurements. In these cases the slides or the strips were placed on top of the cloth.

The counting and measuring of the stains was made with the aid of a microscope, having a magnification of 1 : 20 or 1 : 50.

The size distribution of raindrops with radii larger than 0.2 mm was also measured, using sooted paper. The art-papers, sooted with smoke from kerosene, were horizontally exposed to the rain. Upon contact with the paper, the raindrops produced circular stains, whose size was a function of the diameter of

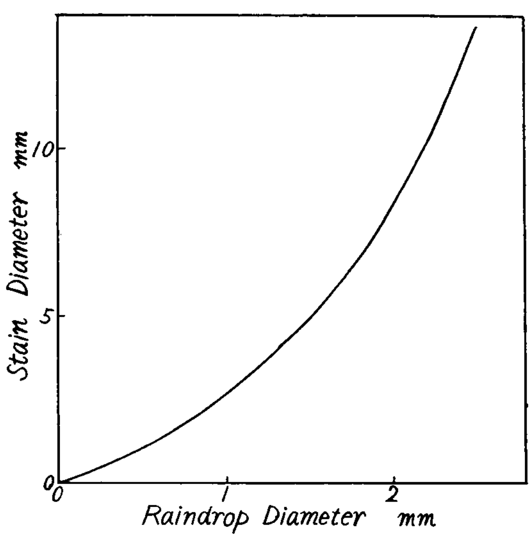

Fig. 4. Relationship of raindrop diameter versus stain diameter on sooted paper.

the original drop. A calibration curve is shown in Fig. 4.

In evaluating the results it has been assumed that the raindrops and the cloud droplets will fall on the slides with terminal velocity v. If the number of drops or droplets hitting 1 cm² of the slide or the film is n_s, the corresponding number of droplets per cm³ of air is

$$n = n_s/v \tag{1}$$

Naturally, turbulent motion in the air will to some extent influence the results of these calculations. The influence may not be too critical, however, as a laminar boundary layer of a thickness of several millimeters will be formed along the plate. In this layer the vertical velocities will be considerably less than the terminal fall velocity of the droplets. According to wind tunnel measurements the boundary layer is always laminar at wind speeds below 4 m/sec. At velocities above 8 m/sec. transition to a turbulent boundary layer will occur, but as the sampling was usually made at wind speeds below 5 m/sec. this case may be excluded (GOLDSTEIN, 1950).

3. Liquid water content check

In order to check the reliability of the sampling technique a comparison was made between

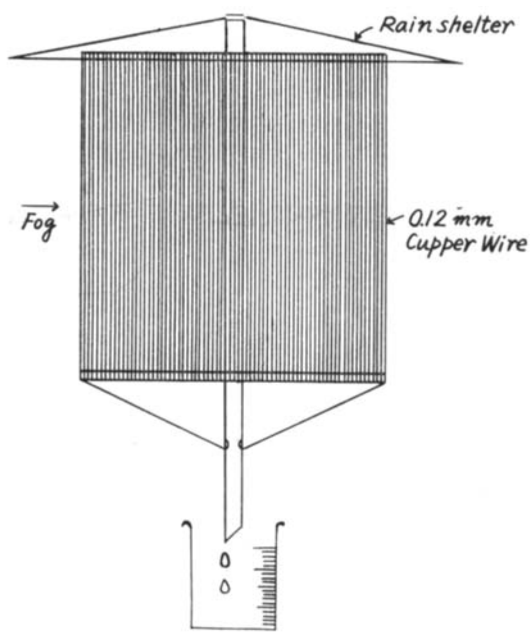

Fig. 5. Cylindrical wire screen.

the cloud liquid water contents determined by this method and those obtained using a wire screen. A cylindrical wire screen shown in Fig. 5 was used to collect the cloud or fog water (TABATA, FUJIOKA and MATSUMURA, 1953). The amount of cloud water ΔM collected in time Δt is represented by the equation:

$$\Delta M = E W_m V A \Delta t \qquad (2)$$

where W_m is the cloud liquid water content, A the cross-section area of the wire screen (174 cm²) and V the wind velocity. According to MATSUMURA (1953) the collection efficiency E is given by $E = 0.11 V^{0.65}$ where V is measured in m/sec.

If n_i is the concentration of cloud droplets of radius r_i per cm³ of the air derived from the equation (1) the total liquid water content W_c is calculated from the equation

$$W_c = \frac{4}{3}\pi\varrho \sum_i r_i^3 n_i$$

where ϱ is the density of water.

A simultaneous measurement of W_m and W_c was made from 1605 to 1615 JST, August 19, 1958, at a station on Mt. Kuro. The water-blue coated celluloid films were horizontally exposed in the cloud for ten seconds every minute. The amount of cloud water collected by the wire screen and the wind velocity were also measured for each minute. The calculated mean value of W_c was 0.39 g/m³, while the wire screen method gave the mean value of W_c of 0.45 g/m³. Considering the low accuracy of cloud liquid water content measurements, the results of these two methods show quite a good agreement. The mean wind velocity was 2.3 m/sec. The typical cloud droplet size distributions during the measurements are shown in Fig. 15. Droplets with radii 5 to 20 microns yielded most of the cloud water.

Measurements were also made in sea fog from 1300 to 1400 JST on July 26, 1952, at Ochiishi on the eastern coast of Hokkaido (Fig. 1, OKITA, 1953). The results shown in Table 1 also indicate close agreement between the fog water contents as determined by these two methods. The wind velocity during the measurements was about 5 m/sec. The fog contained droplets of radii ranging from 2 to 60 microns, but the droplets of radii 5 to 25 microns yielded most of the water.

Table 1. Fog liquid water content g/m³

	No. 1	No. 2
Wire screen method W_m	0.097	0.096
Slide method W_c	0.093	0.109

The above measurements confirm the validity of the new sampling technique for droplets of radii between 5 and 25 microns when the wind velocity is 5 m/sec. or below. In the case of large droplets of radius about 50 microns, no direct confirmation was obtained. It may, however, be supposed that the influence of vertical air motion, even if existing, would be completely negligible for these larger droplets.

In order to determine the limitations of the method for small droplets, a comparison was also made with results obtained when using the impactor method. An impactor with a hole diameter of 1 mm was used. Fig. 6 shows

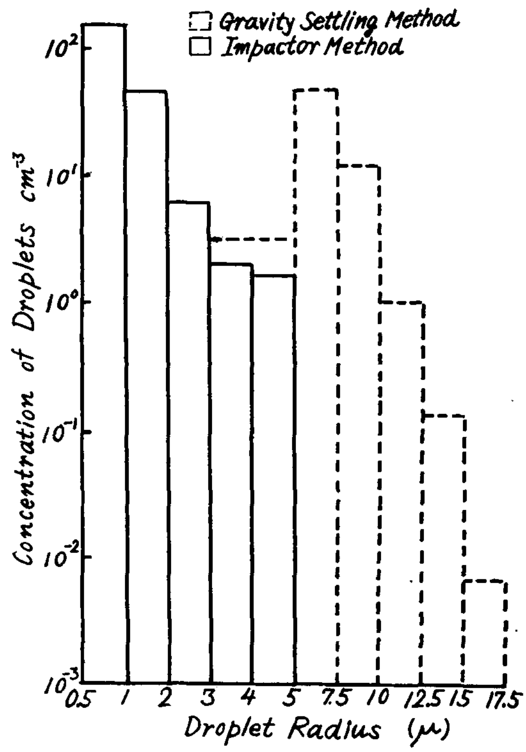

Fig. 6. Droplet size distribution of radiation fog at 2250 JST, Dec. 10, 1959 in Asahikawa.

one example of measured fog droplet size distributions. Both techniques give the same concentration for droplets of radii between 3 and 5 microns. For droplets with radii larger than 5 microns the gravity settling gave larger concentration than the impactor indicating that the collection efficiency of the impactor was reduced for large droplets. The gravity settling method gave inaccurate results for droplets of radii less than 3 microns, obviously due to the fact that the fall velocities of these droplets are too small to give accurate determinations.

4. Measurements in July and August of 1956

During the periods July 25—29 and August 11—14, 1956, an extensive study of cloud droplet size distribution was made on Mt. Kuro. Photographs of the cloud covering Mt. Kuro were also taken at Kamikawa, Kiyokawa or Rikuman (Fig. 2) in order to determine the form and the thickness of the clouds.

(a) July 25

In the early morning (0700 JST) an altostratus cloud with base as high as 2,600 m covered the whole sky but there was no cloud around Mt. Kuro. At about 0810 JST a cumulus cloud formed around Mt. Kuro and soon covered the mountain. At about 0820 JST the cloud tops intruded into the base of the altostratus. On Mt. Kuro drizzle began to fall at 0835 JST. At 0905 JST the altostratus cloud began to break and the tops of the cumulus cloud became visible at 0935 JST. The thickness of the cumulus cloud was about 950 m. From 1000 to 1005 JST the drizzle intensified again. After 1030 JST the drizzle ceased but Mt. Kuro was still covered with cumulus cloud until evening. The vertical development of the cloud was suppressed by a subsidence inversion and the thickness of the cloud varied between 680 and 1,350 m. Drop measurements during this time showed that the most frequent droplet radius was below 25 microns. Three examples of the cumulus cloud droplet size distributions (0845, 1005 and 1320 JST) are shown in Fig. 7.

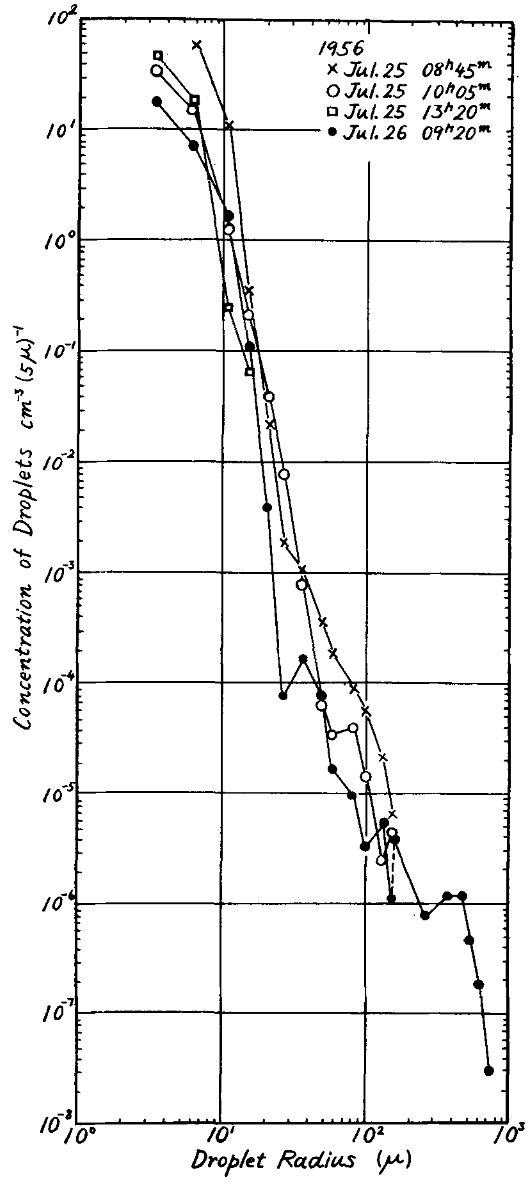

Fig. 7. Droplet size distributions on July 25 and 26, 1956.

Weather at Mt. Kuro:

Jul. 25; Air temperature at 0800 JST was 9.5° C.
Wind direction was ENE to ESE in the morning and N to NW in the afternoon.
Wind velocity was below 2 m/sec.

Jul. 26; Air temperature at 0900 JST was 12.5° C.
Wind direction was SW to NW.
Wind velocity was 0.3 to 2.8 m/sec.

The observations suggest that the drizzle around 0845 JST was induced by the introduction of large cloud droplets at the top of the cumulus cloud. It is uncertain, however, if such a mechanism was also effective for the drizzle occurring around 1005 JST.

(b) July 26

From early morning a light rain fell from nimbostratus clouds, the amount of rain fall being 0.1—0.3 mm/hr. The cloud base was generally several hundred meters above Mt. Kuro and the mountain was hardly covered with cloud. One example of the cloud- and rain-drop size distributions (0920 JST) is shown in Fig. 7.

(c) July 27

Mt. Kuro was covered with nimbostratus cloud throughout the day. Drizzle with maximum drop radii of 0.3 to 0.4 mm was falling continuously now and then accompanied by light rain. Three examples of the droplet size distributions (1025, 1220 and 1435 JST) are shown in Fig. 8.

Simultaneous samplings of cloud- and rain-drops were made from 1025 to 1530 JST at five minute intervals. Fig. 9 shows the variation of the concentrations in four groups of droplets with radii of 4—8.5 microns, 55—90 microns, 0.1—0.2 mm and 0.2—0.3 mm. The rain intensity (above 0.1 mm/hr) and the radii of largest raindrops are shown at the bottom of the figure.

Observations of the vertical variation of raindrop size distribution (OKITA, 1958 b) have shown that, when the rate of rainfall exceeds 1 mm/hr, the concentration of small drops with radius 0.05—0.25 mm decreases rapidly from the cloud base downwards due to mutual coalescence. As this type of process would certainly also take place in the cloud itself, one may from Fig. 9 infer that a considerable number of the raindrops of this size were formed within a layer of perhaps 1,000 m thickness above the station. As the air temperature at Mount Kuro on this occasion varied between 13.0 and 14.4° C, the production of the drops occurred at temperatures well above freezing.

(d) July 28

In the early morning Mt. Kuro was covered by nimbostratus cloud, which gradually transformed into cumulus around 0900 JST, the thickness being between 1,100 and 2,000 m.

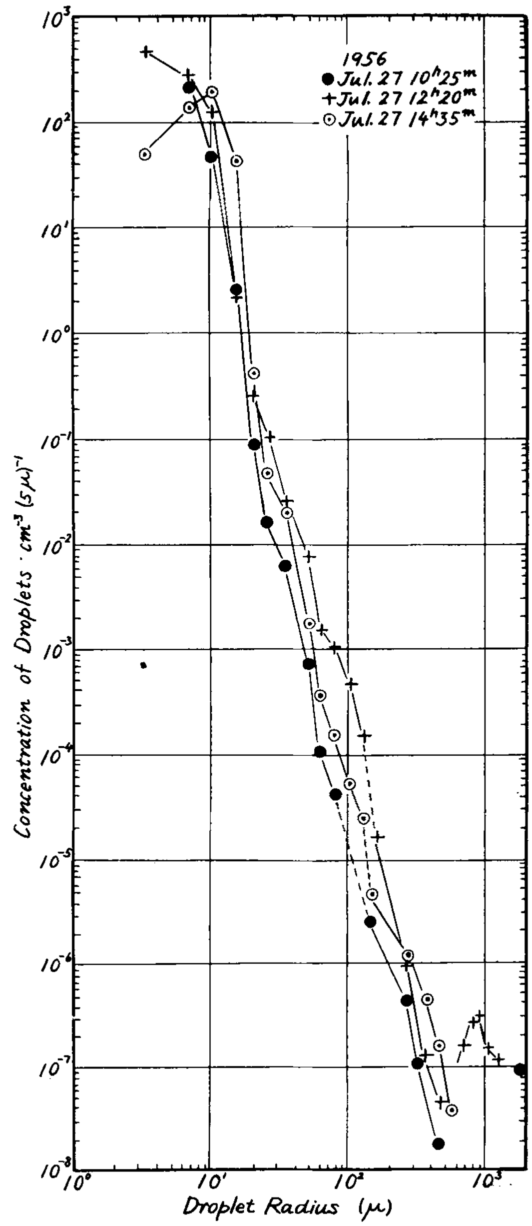

Fig. 8. Droplet size distributions on July 27, 1956.

Weather at Mt. Kuro:

Air temperature was between 13.0 and 14.4° C.
Wind direction was W but it turned to NW after 1500 JST.

Wind velocity was 2.8 to 5.8 m/sec.

The size distribution of the cloud droplets at 0900 JST is shown in Fig. 10.

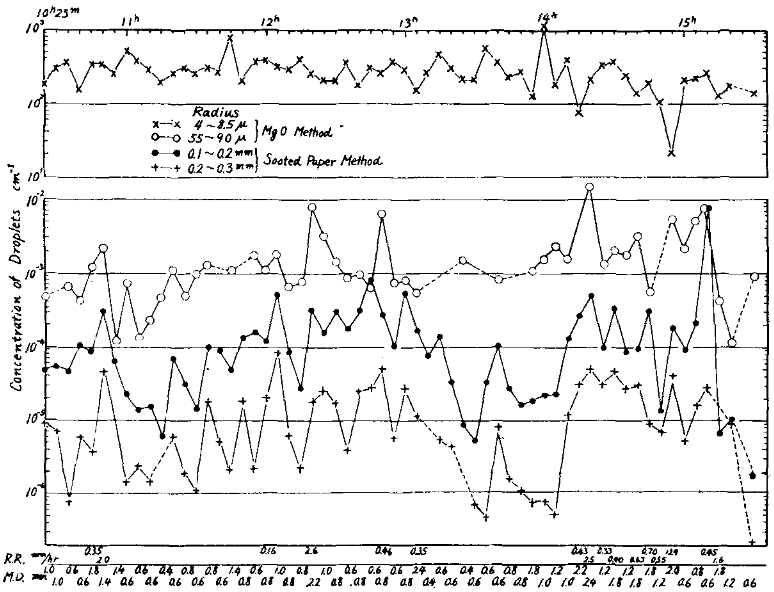

Fig. 9. Variation of droplet concentrations on July 27, 1956.
R. R.: Rate of rainfall
M. D.: Maximum drop diameter

(e) July 29

From early morning Mt. Kuro was covered by cumulus or cumulonimbus clouds. With rising cloud base the station came into cloud-free air at 1100 JST. Rain started at 1150 JST and continued until 1800 JST. Two examples of the cloud droplet size distributions (0945 and 1505 JST) are shown in Fig. 10.

(f) August 12

From early morning cumulus or cumulus congestus clouds, formed over the west side of Mt. Asahi and moved in over Mt. Kuro. From 1235 to 1300 JST drizzle fell on the mountain. The thickness of the cloud estimated from photographs was about 3,000 m. The air temperature at the cloud top, estimated from Wakkanai and Sapporo radiosonde data was about 0° C, and the drizzle was thus produced in the cloud at temperatures above freezing. The droplet size distribution at 1235 JST is shown in Fig. 11. Drizzle with maximum drop radius of 0.3 mm also fell from 1740 JST, when the thickness of the cumulus congestus cloud was about 3,000 m.

(g) August 13

Mt. Kuro was covered with nimbostratus clouds throughout the day. Light rain or drizzle fell continuously with a rate of 0.2 to 0.3 mm/hr. Two examples (1155 and 1415 JST) of the drop size distributions are shown in Fig. 11.

(h) August 14

Mt. Kuro was covered with nimbostratus clouds as on the preceding day, the precipitation continuing in the form of intermittent rain. Two examples (0455 and 1505 JST) of drop size distributions are shown in Fig. 11.

A continuous sampling of both cloud- and rain-drops was made from 0500 to 0710 JST as on July 27. The result is shown in Fig. 12. It is of interest to note that the increase in concentration of large cloud droplets as well as of small raindrops occurred concurrently with increasing rainfall intensity (e.g. 0530 to 0545 JST and after 0640 JST). These large cloud droplets or small raindrops are supposed to be formed at the lower part of the cloud under a rain generating cell.

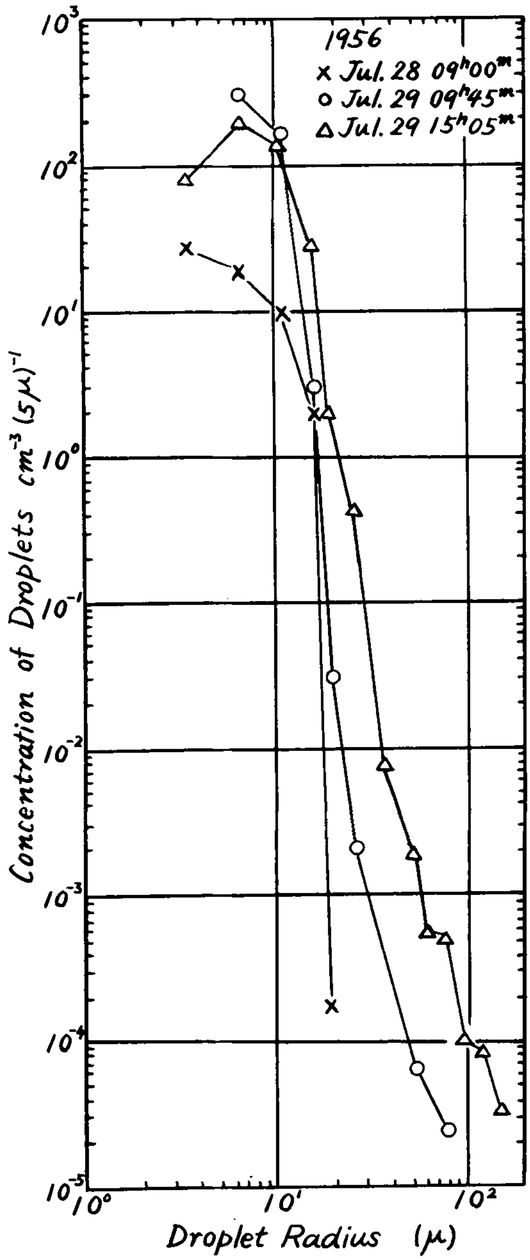

Fig. 10. Droplet size distributions on July 28 and 29, 1956.
Weather at Mt. Kuro:

Date	July 28	July 29
Air temperature °C	13.0—15.5	12.0—14.5
Wind direction	WSW—W	W—WNW
Wind velocity m/sec	3.3—5.9	1.9—4.3

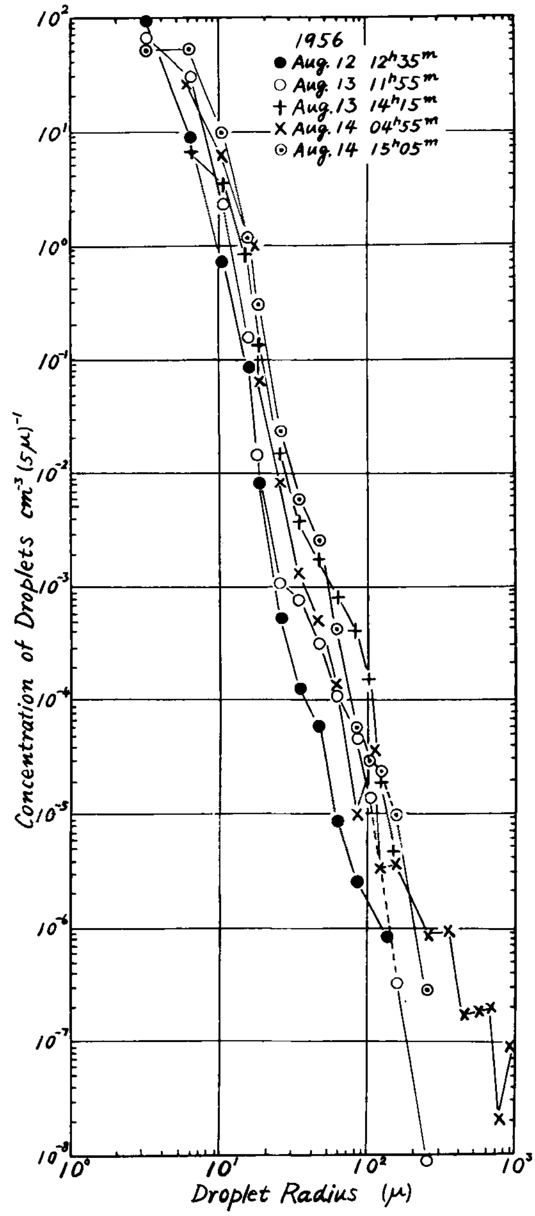

Fig. 11. Droplet size distributions on August 12, 13 and 14. Weather at Mt. Kuro was as follows:

Date	Aug. 12	Aug. 13	Aug. 14
Air temperature °C	15.0—20.4	14.2—17.0	11.5—17.5
Wind direction	W—SW	SW—WSW	SW—WSW
Wind velocity m/sec	1.7—3.5	1.1—3.0	0.7—5.2

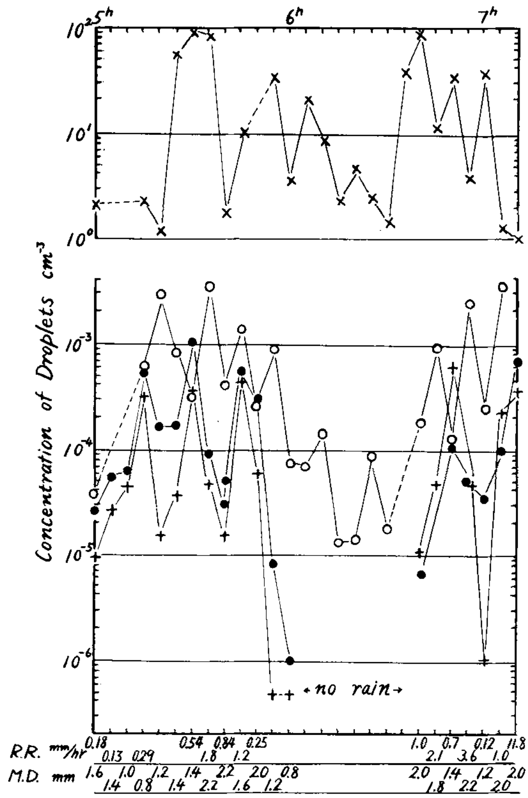

Fig. 12. Variation of droplet concentrations on August 14, 1956. Symbols are the same as in Fig. 9.

5. Measurements in August of 1955, 1957 and of 1958

(a) *August 17 and 19, 1955*

Simultaneous samplings of cloud- and rain-drops were made on several occasions on Mt. Kuro on August 17 and 19, 1955. Some of the cloud- and rain-drop size distributions are presented in Fig. 13 (cf. OKITA, 1958 b).

(b) *August 23, 1957*

Light showers from cumulonimbus clouds fell from midnight of August 22. Samplings were made from 0600 to 0900 JST. Four size distribution curves are presented in Fig. 14.

(c) *August 19, 1958*

Fig. 15 shows two examples of cloud droplet size distributions on August 19, 1958, when measurements of cloud liquid water content also were made (see Paragraph 3).

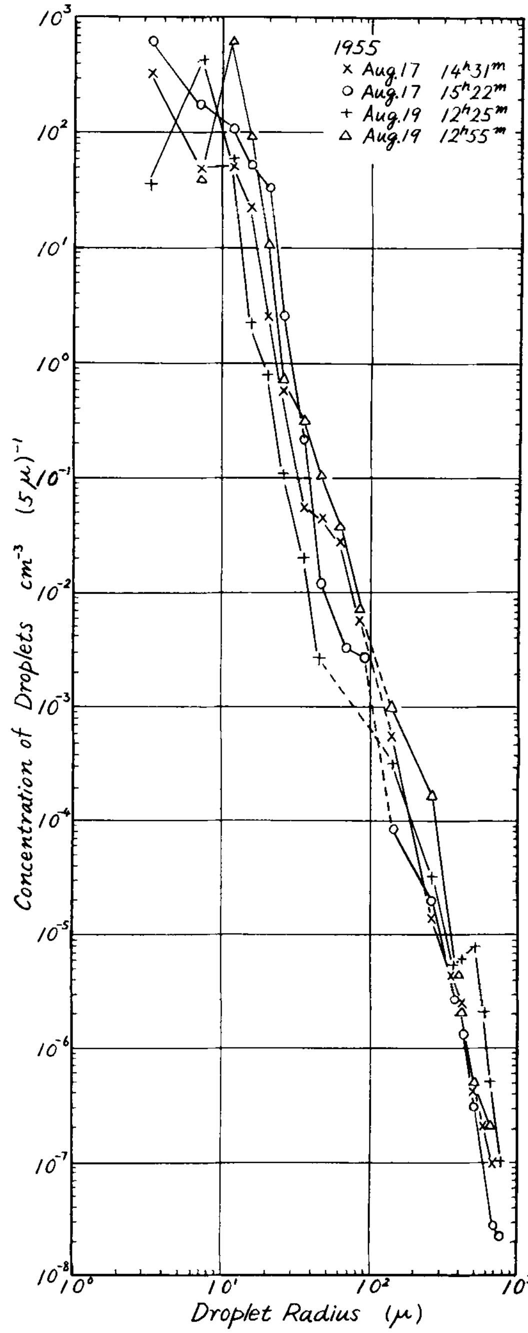

Fig. 13. Droplet size distributions on August 17 and 19, 1955.

Weather at Mt. Kuro:

Date	Aug. 17	Aug. 19
Air temperature °C	—	12.6
Wind direction	WNW—NW	WSW—W
Wind velocity m/sec	1.3—4.7	5.5—9.9

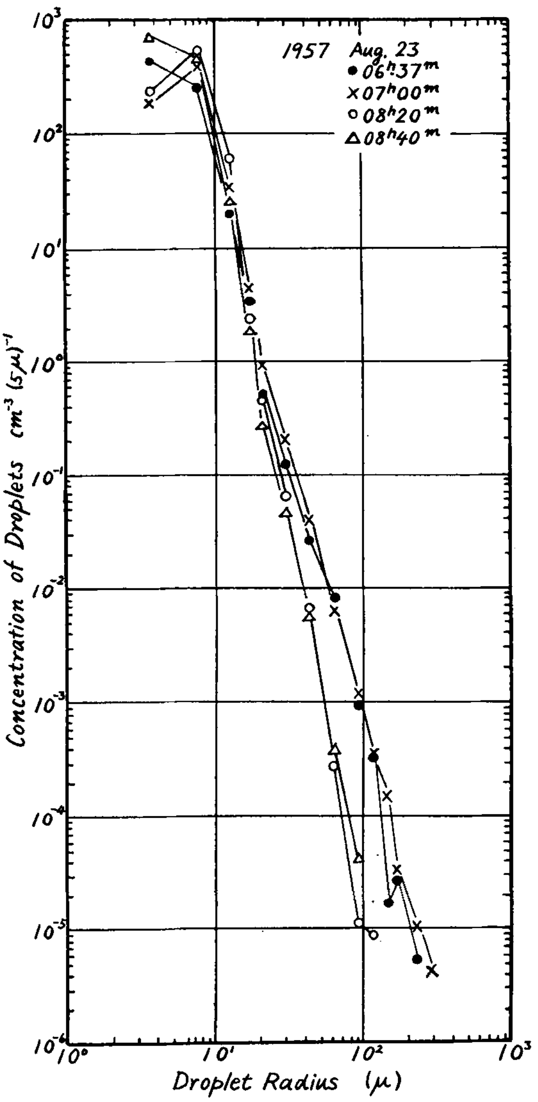

Fig. 14. Droplet size distributions on August 23, 1957.

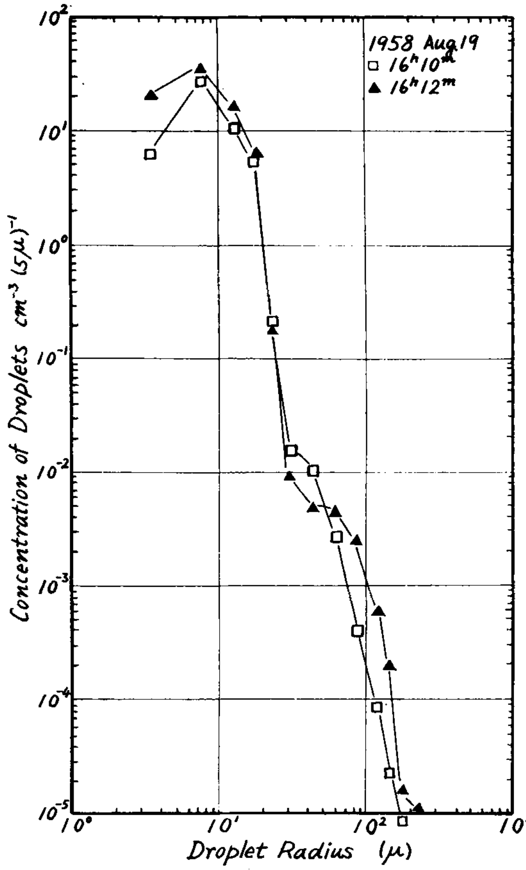

Fig. 15. Droplet size distributions on August 19, 1958.
Weather at Mt. Kuro:
Air temperature was 12.0° C.
Wind direction was S.
Wind velocity was 2.3 m/sec.

6. Some characteristics of drop size distribution curves

The cloud- and rain-drop size distributions represented by Figs. 7, 8, 10, 11, 13, 14 and 15 show several characteristic features. In general the distribution curves for each day have similar forms. The size distributions on August 17 and 19, 1955 and on August 23, 1957 are represented by almost straight lines in the log N-log r graph, where N is the concentration calculated for 5 micron radius intervals and r the droplet radius. These distributions may therefore be represented by the relation

$$N = N_0\, r^{-\alpha} \qquad (3)$$

The values of N_0 and α of some representative size distributions are listed in Table 2. It is of interest that on August 23, 1957 α had constant values of about 5.1 up till about 0800 JST but then suddenly changed to a value around 6.8.

The distribution curves for the other days deviate somewhat from a straight line, especially the curves for July 25 and 26, 1955 and for August 19, 1958, show a sharp bend. It has been assumed, however, that these distributions should also be expressible by the equation (3) and the corresponding approximate values of

Table 2.

Date	Time (JST)	N_0	α	Range of r (μ)	L.W.C. g/m³	R mm/hr	Number of droplets m⁻³ Radius (μ) 50—125	125—250	250—400	Cloud form
Aug. 17, 1955	1145	$1.2 \cdot 10^{-13}$	4.9	8.5—600	1.20	2.6	48,000	15,400	730	Ns
	1230	$2.5 \cdot 10^{-12}$	4.2	3—750	0.83	3.0	57,000	15,300	630	»
	1431	$6.7 \cdot 10^{-13}$	4.6	3—750	1.03	1.0	168,000	4,500	180	»
	1522	$7.9 \cdot 10^{-14}$	4.9	3—750	2.56	0.46	49,000	1,300	150	»
Aug. 19, 1955	1218	$7.9 \cdot 10^{-15}$	5.3	3—800	1.73	2.7	27,000	21,000	5,100	Cb
	1225	$2.1 \cdot 10^{-12}$	4.5	3—850	0.85	1.6	14,200	3,200	280	»
	1255	$9.6 \cdot 10^{-14}$	5.3	8.5—700	4.5	0.68	280,000	11,700	430	»
July 25, 1956	0835	$2.4 \cdot 10^{-16}$	5.5	3—175	0.14	—	350	11	—	Cu
	0845	$1.3 \cdot 10^{-14}$	4.9	3—175	0.12	—	1,600	60	—	»
	0930	$1.8 \cdot 10^{-17}$	5.9	3—125	0.18	—	520	—	—	»
	1005	$1.4 \cdot 10^{-14}$	4.7	3—175	0.025	—	320	18	—	»
	1015	$1.0 \cdot 10^{-21}$	7.2	3— 50	0.18	—	—	—	—	»
	1320	$1.8 \cdot 10^{-21}$	6.9	3— 17	0.021	—	—	—	—	»
	1540	$2.7 \cdot 10^{-27}$	9.4	8.5— 30	0.15	—	—	—	—	»
	1655	$1.0 \cdot 10^{-26}$	9.1	3— 25	0.35	—	—	—	—	»
July 26, 1956	0920	$5.5 \cdot 10^{-13}$	4.1	3—750	0.016	—	150	60	37	Ns
July 27, 1956	1025	$2.5 \cdot 10^{-15}$	5.3	3—500	0.43	0.014	770	35	4.9	»
	1050	$1.0 \cdot 10^{-13}$	4.9	3—700	0.89	2.0	3,400	270	13	»
	1145	$1.8 \cdot 10^{-17}$	6.2	3—300	1.7	$8.5 \cdot 10^{-3}$	1,560	28	—	»
	1220	$9.0 \cdot 10^{-18}$	5.2	3—500	0.87	2.6	11,700	430	8.1	»
	1250	$2.3 \cdot 10^{-16}$	5.8	3—400	0.94	0.46	9,400	440	11	»
	1405	$4.3 \cdot 10^{-17}$	6.2	8.5—600	0.79	$2.8 \cdot 10^{-3}$	2,600	25	0.25	»
	1435	$1.5 \cdot 10^{-15}$	5.7	8.5—600	1.5	0.062	2,600	124	18	»
	1510	$5.1 \cdot 10^{-16}$	5.7	3—350	1.0	0.45	8,400	900	7.5	»
July 28, 1956	0900	$3.0 \cdot 10^{-33}$	11.0	3— 25	0.056	—	—	—	—	Cu
July 29, 1956	0910	$1.1 \cdot 10^{-20}$	6.6	3— 50	0.022	—	—	—	—	Cb
	0945	$1.5 \cdot 10^{-29}$	10.1	3—100	0.95	—	180	—	—	»
	1025	$4.7 \cdot 10^{-24}$	8.0	3— 30	0.27	—	—	—	—	»
	1155	$5.7 \cdot 10^{-24}$	7.6	3— 35	0.014	—	—	—	—	»
	1505	$5.3 \cdot 10^{-14}$	4.9	3—175	1.2	—	4,600	280	—	»
	1605	$2.5 \cdot 10^{-18}$	6.2	3— 75	0.42	—	650	—	—	»
Aug. 12, 1956	1235	$2.3 \cdot 10^{-17}$	5.5	3—150	0.016	—	60	3.8	—	»
Aug. 13, 1956	1155	$1.1 \cdot 10^{-17}$	5.8	3—250	0.043	$5.0 \cdot 10^{-4}$	720	5.4	—	Ns
	1415	$1.0 \cdot 10^{-14}$	4.9	3—250	0.047	0.28	5,000	136	—	»
Aug. 14, 1956	0455	$5.7 \cdot 10^{-13}$	4.3	3—800	0.067	0.31	870	49	2.5	»
	0605	$1.2 \cdot 10^{-17}$	5.7	3—300	0.048	$4.4 \cdot 10^{-4}$	107	2.5	—	»
	0840	$1.7 \cdot 10^{-15}$	5.1	10—500	0.058	0.23	1,130	450	20	»
	0930	$7.8 \cdot 10^{-15}$	4.9	3—400	0.081	0.016	1,460	17	6.2	»
	1025	$3.2 \cdot 10^{-20}$	4.6	3—175	0.043	0.12	4,600	80	—	»
	1335	$4.4 \cdot 10^{-15}$	4.8	3—125	0.048	—	480	—	—	»
	1505	$7.3 \cdot 10^{-16}$	5.3	3—300	0.13	0.015	2,400	113	—	»
Aug. 23, 1957	0637	$3.6 \cdot 10^{-14}$	5.1	3—250	0.86	—	47,000	410	—	Cb
	0700	$3.3 \cdot 10^{-14}$	5.2	3—300	1.34	—	38,000	1,320	44	»
	0820	$4.0 \cdot 10^{-19}$	6.8	3—125	1.57	—	1,700	—	—	»
	0840	$3.1 \cdot 10^{-18}$	6.5	3—100	1.17	—	2,200	—	—	»
Aug. 19, 1958	1610	$1.6 \cdot 10^{-13}$	4.6	3—175	0.33	—	17,000	105	—	Ns
	1612	$3.4 \cdot 10^{-14}$	4.8	3—225	0.46	—	40,000	1,220	—	»

N_0 and α are also listed in Table 2. The cloud liquid water contents in Table 2 are calculated from the size distribution curves and the rainfall intensities by using the sooted paper method.

The effects of cloud form and rain on the

Table 3.

	Maximum drop radius (μ)				Cloud form
	< 50	50—250	250—500	500 >	
Mean value of α	—	5.4	5.7	4.8	Ns
Range of α	—	4.6—6.8	4.9—7.3	4.1—6.2	
Number of samples	0	10	14	10	
Mean value of α	8.4	6.4	5.2	5.0	Cb
Range of α	6.6—10.0	4.9—10.1	5.2	4.5—5.3	
Number of samples	13	8	1	3	
Mean value of α	8.1	5.8	—	—	Cu
Range of α	4.6—13.1	4.7—6.7	—	—	
Number of samples	16	7	0	0	

value of α are demonstrated in Table 3. In this table 82 size distribution samples including those shown in Table 2 are classified according to cloud form and maximum drop radius in the distribution. The table indicates that the mean value of α is smallest with rain of moderate intensity, in which raindrops with radius larger than 0.5 mm exist. This is because the concentrations of large cloud droplets or small raindrops are large (August 17 and 19, 1955; July 27, 1956) or because the clouds have relatively few small droplets (July 26, 1956). When drizzle or light rain falls inside the cloud the value of α is between 5.2 and 6.4. For non-precipitating clouds its value is largest (8.1—8.4). There is of course a large variability of α between individual distributions and there seems to be no distinct difference in the α-values for various cloud forms.

Large cloud droplets with radii above 50 microns are always found in nimbostratus clouds (August 17, 1955; July 26 and 27, August 13 and 14, 1956; August 19, 1958). In cumulonimbus or cumulus congestus about half of the size distributions show such large droplets (August 19, 1955; July 29 and August 12, 1956; August 23, 1957). These were also found in cumulus cloud when the top had been seeded from higher clouds (July 25, 1956). On the other hand, in cumulus clouds of thickness less than 2,000 m and with no surrounding clouds no droplets of radius above 25 microns were found (July 28, 1956).

The observations on July 27 and on August 12 and 14 in 1956 further suggest that the large droplets are formed in the part of the cloud where the air temperature is above freezing.

Brown and Braham (1959) made aeroplane observations of large droplets in tropical cumuli. The curves A and C in Fig. 16 show their narrow and broad distributions respectively. The size distribution B—R in the figure is the one obtained by Battan and Reitan (1957) in tropical cumuli. No determination was made of droplets with radii between 50 and 100 microns. If it is assumed that the size dristibution of these droplets be represented by the broken line in the figure. The corresponding values of α in tropical cumuli are 6.7 and 5.0 for A and C distributions respectively. These values are in good agreement with those given in Table 3 for cases when the largest droplet radius is between 50 and 250 microns. In Fig. 16 the size distributions in fair weather cumulus and cumulonimbus clouds obtained by Weickmann and Aufm Kampe (1953) are also shown. The corresponding values of α are about 5 and 3 for fair weather cumuli and cumulonimbus clouds respectively. These values are much smaller than the values of α given in Table 3 in the corresponding cases.

7. Concentration of large cloud droplets

The concentrations of large cloud droplets with radii above 50 microns are shown in columns 8—10 of Table 2. There is great variability in the concentration and no significant difference seems to exist between cumulonimbus and nimbostratus clouds. In the cumulus clouds of July 25, 1956 the concentration of droplets of radius 50 to 125 micron varies between 320 and 1,200 m^{-3}.

The concentrations of large droplets in tropical cumuli and in cumulus and layer clouds over England are given in Table 4 (Blanchard, 1957; Murgatroyd and Gar-

Table 4. Concentrations of large droplets in tropical cumuli and in cloud over England.

Investigator	Concentration m^{-3}	Size interval mm	Type of Cloud
Bowen	17,150	0.2—1.6	Tropical cumuli
Brown and Braham	1,492 (mean) 7,581 (max.)	0.15—0.65	Tropical cumuli
Murgatroyd and Garrod	91,600 (max.)	> 0.1	Cold cumuli, England
	6,690 (max.) 16,800 (max.)	> 0.1 > 0.1	Warm cumuli Mixed Cu and Sc
Singleton	40—18,000	0.1—0.25	Layer clouds, England
Blanchard	59,000—83,000	0.1—0.34	Hawaiian cumuli

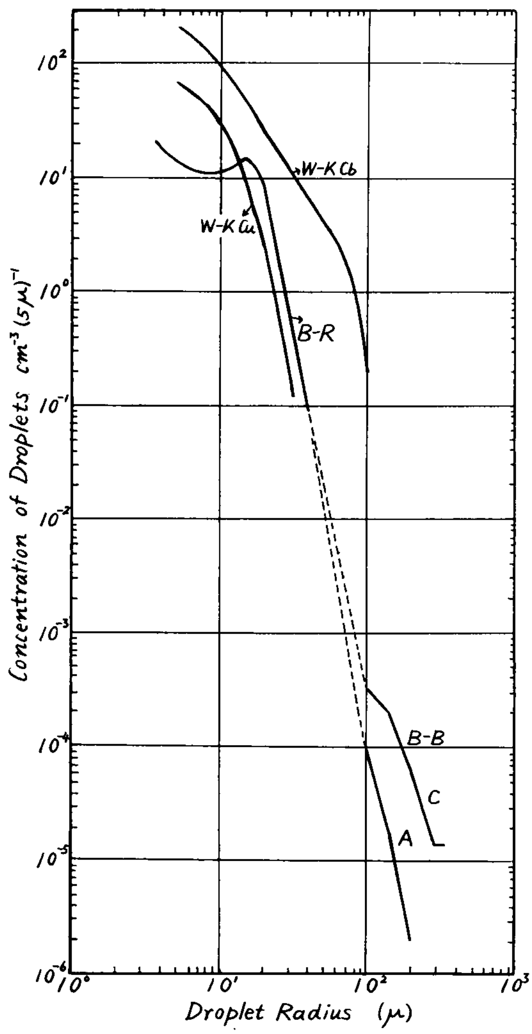

Fig. 16. Droplet size distributions.

W—K Cb: WEICKMANN and AUFM KAMPE, cumulonimbus cloud

W—K Cu: WEICKMANN and AUFM KAMPE, cumulus cloud

B—R: BATTAN and REITAN

B—B: BROWN and BRAHAM

ROD, 1960; SINGLETON, 1960). The concentrations found in Table 2 are generally of the same order of magnitude. On four days (August 17 and 19, 1955; August 23, 1957; August 19, 1958) the concentrations exceeded 40,000 m^{-3} and on August 17 and 19 in 1955 concentrations above 100,000 m^{-3} were found in precipitating clouds. Blanchard also found numerous large droplets in Hawaiian warm cumuli, and according to the experience of the author such high concentrations of large droplets frequently occur in heavily or moderately precipitating clouds.

8. Conclusion

The observations of cloud- and rain-drop size distributions reveal that even in a temperate latitude a considerable number of large droplets of radii above 50 microns are contained in nimbostratus and cumulonimbus and even in cumulus clouds. Some observational results further suggest that these large droplets are formed in the warm part of the cloud where the air temperature is above freezing.

These droplets would be formed by condensation-coalescence process. WELANDER (1959) calculated the effect of coalescence on the droplet size distribution and deduced that both in the "time-dependent" and in the "steady state" cases the spectra could be approximated by a power law, r^{-5} and r^{-3} respectively. He further stated that the transient model leading to the r^{-5}-law should apply best to "young" clouds such as fair weather cumuli while the steady state model should hold for "older" clouds such as cumulonimbus or cumulus congestus. The theory was confirmed by observations made by Weickman and Aufm Kampe. However, our observations indicate that the value of the parameter α lies between 5.2 and 6.4 for "older" clouds (nimbostratus and cumulonimbus clouds) and between 8.1 and 8.4 for "young" clouds (cumuli). The discrepancy may be due to the presence of giantnuclei or to other factors.

Acknowledgements

Financial supports of this project by the Hokkaido Electric Power Company and by the Department of Education are gratefully acknowledged. The author is grateful to the members of the Institute of Low Temperature Science, Hokkaido University, for kindly lending him a fog liquid water content meter.

REFERENCES

BATTAN, L. J., and REITAN, C. H., 1957: *Droplet size measurements in convective clouds. Artificial Stimulation of Rain.* Pergamon Press, New York, pp. 184—191.

BLANCHARD, D. C., 1957: *Discussion of raindrop distributions made during project shower, Hawaii,* 1954. ibid., pp. 213—223.

BROWN, E. N., and BRAHAM, R. R., 1959: Precipitation-particle measurements in trade-wind cumuli. *Journal of Met.*, **16**, p. 609.

GOLDSTEIN, S., 1950: *Modern Developments in Fluid Dynamics,* Oxford Clarendon Press, London. **I**, p. 326.

MATSUMURA, N., 1953: *On the calibration of a fog meter. Studies on Fogs,* Tanne Trading Co. Ltd., Sapporo, pp. 175—186.

MURGATROYD, R. J., and GARROD, M. P., 1960: Observations of precipitation elements in cumulus clouds. *Quart. Journal Roy. Met. Soc.*, **86**, p. 167.

OKITA, T., 1953: On the mechanism of dissipation of fog by model wood. *Journal Met. Soc., Japan,* **31**, pp. 237—247.

OKITA, T., 1958 a: *Water-blue film method for measurement of cloud and fog droplets.* ibid., **36**, pp. 164—165.

OKITA, T., 1958 b: Observations of vertical change of raindrop size distribution. *Science Report Tohoku University, Geophys.*, **10**, pp. 1—14.

PRANDTL, L., and TIETJENS, O., 1931: *Hydro- und Aeromechanik,* Berlin.

SINGLETON, F., 1960: Aircraft observations of rain and drizzle from layer clouds. *Quart. Journ. Roy. Met. Soc.*, **86**, p. 195.

TABATA, T., FUJIOKA, T., and MATSUMURA, N., 1953: *On a recording fog meter. Studies on Fogs,* Tanne Trading Co. Ltd., Sapporo, pp. 169—173.

WEICKMANN, H. K., and AUFM KAMPE, H. J., 1953: Properties of cumulus clouds. *Journ. Met.*, **10**, pp. 204—211.

WELANDER, P., 1959: A theoretical power law for the size distribution of small particles or drops falling through the atmosphere. *Tellus*, **11**, pp. 197—201.